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ID Notification (PTD)

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To: Paul J. Shustack

cc: Tom M. Leslie, Subcommittee Chair

From: Mary Y. Redman

Date:

Re: D15659—Forming polymer waveguides by end-fire curing

This Invention Disclosure (ID) has been given ID No. **15659** and assigned to the **Polymers** Technology Subcommittee for evaluation (and possibly copied to other Subcommittees for comment). The Subcommittee Chair is **Tom M. Leslie,** to whom any questions regarding this ID should be directed. Use this ID Number **15659** on *all* communications relating to this invention.

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— **What You Should Do Now** —

- Review any information (articles, patents, competitors' announcements, related IDs, etc.) that might be helpful in understanding the invention, its commercial potential, or patentability. Forward a copy of that information to the Subcommittee Chair *and* the Patent Department *with the ID Number on it.* Include your memo, note, or e-mail describing the relevance of those references.

  Identify any "prior art" known to you, which is related or similar to your invention. Include similar ideas used for different purposes, or dissimilar ideas that have the same function. Do not attempt to decide if a reference is "prior art" on your own. That decision will be made later by the Patent Department. You must also identify previous work by another Corning Incorporated employee (or a non-employee) that is related or similar to your invention which you knew about *before or at the time you conceived of your invention.*

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- Prepare, collect, and save a detailed description of how to *make* and *use* the invention (or how to practice any process), including any data, sketches, prototypes, samples, photographs, videos, or technical drawings.

Thank you!

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INVENTION DISCLOSURE

Division: Science & Technology

Project Code: ____________

Patent Dept. Use Only

Disclosure No. 15659

Attorney: MYR

Action Copy to:

CW Deneka
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Subcommittee Chair: TML
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To: Patent Dept. SP FR-2-12
cc: C.W. Deneka

Title of Invention: **MAXIMUM 50 CHARACTER SPACES**

Forming polymer waveguides by end-fire curing

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Commercial Focus: Specify the Division (e.g. TPD, EPD, or SPD) and product line (if any) which would have the primary interest in this invention.

Division TPD Business/Product LOC-Athermalization

Relevant Records: Identity notebooks, reports or memos which refer to this invention.

[illegible]

If the invention is a product, has a product embodying the invention been sold or offered for sale? No

If the invention is a process or an apparatus, has it been used to make a product which was sold or offered for sale? No

Has the invention been disclosed to anyone outside Corning? No

If yes to whom? ____________

Was the disclosure under a Confidentiality Agreement? No

Description of Invention: Write and attatch a description of your invention. Start with the Background of the Invention, i.e., to what area does it relate, what problem does it solve, and how does it differ from what has been done before? Then, provide a sufficient description of the invention, including drawings if appropriate, so that someone not familiar with the invention will understand what it is, how it works, and how it solves the problem.

ALL ATTACHMENTS MUST BE SIGNED IN INK, DATED AND WITNESSED BY SOMEONE WHO UNDERSTANDS THE INVENTION

Signatures: Inventor(s) [signature] Steven Dawes Date ____
[signature] Michael DeRosa Date ____
[signature] Jianguo Wang Date ____
[signature] Robert Hagerty Date ____

Witness [signature] Date ____

Dept. Manager [signature] Date ____

The invention

A method for reducing loss in optical systems that include a region of free space optical propagation by writing low loss waveguides in polymeric material bridging the free space region. The waveguide is formed by propagating an ultraviolet beam along one or preferably both arms of a waveguide system and launching an UV beam into the polymer filling the free space part of the device. The concentrated UV beams cure the polymer, inducing a positive index change, until the two beams meet midway between their inputs. The process is called end-fire curing of the polymer.

In particular, two applications are presented, low cost athermalization of planar WDM devices, and low loss coupling of fibers having differential optical and/or physical properties.

A method for low cost athermalization of planar WDM whereby negative dn/dT waveguide is formed in a region of a phase array by illumination of a filling photosensitive polymer through the arrayed waveguides. Preferably the region is a wedge shaped groove etched out of the array that is filled with a photosensitive polymer. UV light is launched into both the input and output sides of the polymer filled region that induces a differential cure in the illuminated zone. The polymer is formulated such that the cure induces an increased index of refraction so that a waveguide is established in the polymer between the input an output arms of the glass waveguides. This in-situ process of writing a polymeric waveguide can reduce loss by a factor of 3 or more across a 150 micrometer wide region.

Background

Planar wavelength division multiplexers based on a phase array design executed in silica based glasses show a significant temperature shift in the output channel positions due to variations in optical path length in the phase array. The device relies on designed OPL differences in the array to effect a grating and separate a single broad band input light source into several narrow band channels. The temperature dependence of the center channel wavelength position arises from optical path length shifts with temperature due to non zero CTE and dn/dT of the glass. The center channel wavelength may vary by as much as 0.01 nm/°C compared to typical device specifications of <0.001nm/°C. Currently Corning uses an actively controlled temperature packaging concept to meet stability specifications, but it is strongly desired to have a passively athermalized device.

Athermalization for planar WDM devices requires some form of correction of the temperature dependent phase shift in silica phase arrays. Notably, a method that can be used is to etch a groove in the phase array region and fill it with an optically transmitting material have large negative dn/dT.[1] The dimensions of the groove are such that light propagating through each arm of the phase array is compensated by a proportional path though the negative dn/dT material so that the thermally induced optical path length change is zero. The basic elements of the optical design to compensate for thermally derived optical path length effects have been presented.[1-4] The key issue is that the groove region is lossy due to diffraction though the free space region defined by the groove. Loss reduction by using multiple grooves is possible,[3] but with the disadvantage of backreflection and potentially high crosstalk. Loss reduction by formation of slab waveguides in the groove has also been proposed but is costly to manufacture.[4] This invention describes a novel low cost approach to the problem of minimizing loss.

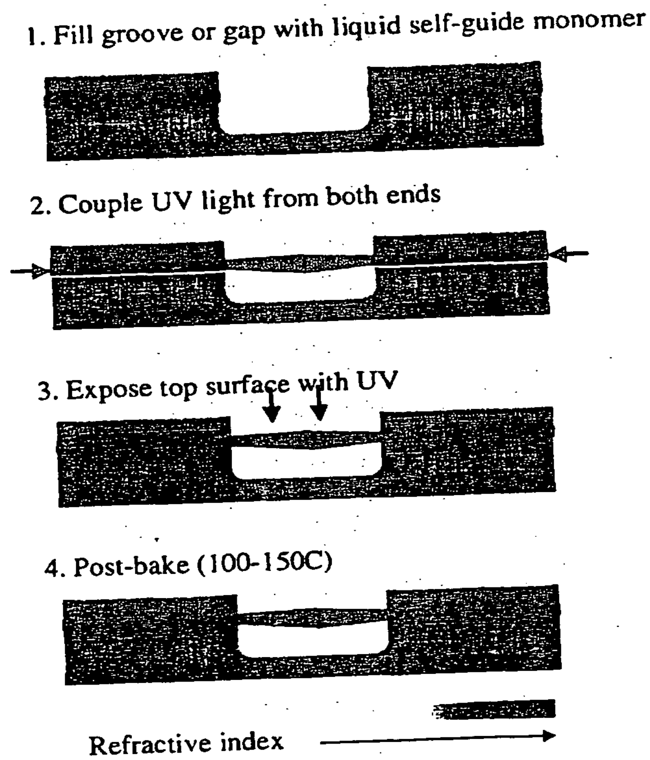
Fiber to fiber splicing is a critical process step in the fabrication of many devices, and is especially difficult to do when material properties of the two fibers are significantly different from one anther. An extreme example is the coupling of a low temperature high expansion XBLAN amplifier fiber to a refractory, low expansion long haul transmission fiber. Conventional fusion splicing techniques can not be employed. The fabrication of a generic fiber to fiber splice

requires the two optical fibers to be actively aligned near a substrate with the ends separated by between 5 and 150 microns.

The fiber end-fire UV curing technique has been reported in the literature for making short step index type optical interconnect waveguides between fibers or a fiber and a device[5]. End-fire UV curing has also been employed to improve bonding of fibers to planar waveguide structures as an alternative to using a flood UV lamp[6-9]. The end-fire technique ensures that the UV light is curing the adhesive at the precise interface between the two cores of the waveguiding region. Finally, UV end-firing has also been used to make unique photocurable lens-like structures at the end of optical fibers[10].

Details of the invention

The general process disclosed for making the low loss coupling of waveguides separated by a "free-space" gap is schematically shown here.



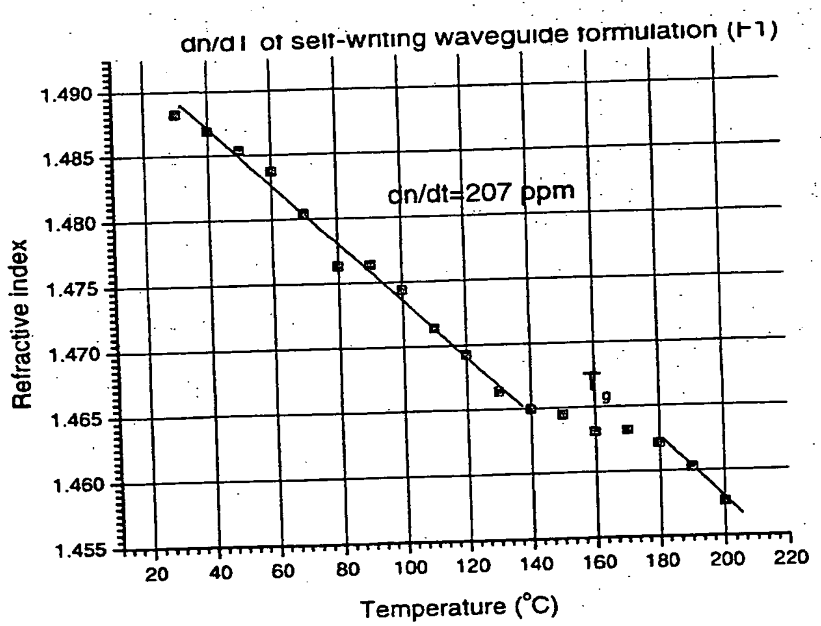
In the case of an athermalized phasar device the process "writes" an optical waveguide in the polymer filled groove between the two silica waveguiding regions. The short waveguide is intended to dramatically reduce the insertion loss and improve overall performance relative to the device operating with free space propagation through the groove. Optimally, two optical fibers are coupled to the input and output waveguides so that the polymer in the groove is irradiated by

UV from both sides simultaneously. In a phasar, the UV beam is launched into the individual arms of the phase array through the slab waveguides. The UV is launched into the polymer from both sides of each arm in the waveguide simultaneously, and the intensity profile of the guided beam initiates photopolymerization. In the photopolymerized region the index is higher than in the surrounding region. The final product is a cylindrically symmetrical waveguiding region that improves the optical coupling between the two silica waveguides across the polymer filled gap.

The process disclosed for making fiber to fiber "splices" writes a waveguide between two aligned fibers. The polymer is applied across the two ends of the fiber, and the UV end-fire curing technique was used to cure the photopolymer in a specific region. Optimally, the UV is launched through both optical fibers so that the polymer gets irradiated by UV from both sides simultaneously. As the UV light exits the fibers the two UV beams overlap and the intensity profile initiates photopolymerization. In the photopolymerized region the index is higher than in the surrounding region. The final product is a cylindrically symmetrical waveguiding region that improves the optical coupling between the two silica waveguides across the polymer filled gap. (See Figures 1 and 2)

To enable these processes the polymer must have the property that upon initial exposure to light a high index (core)region is formed, preferably by virtue of a permanent compositional change. Subsequent curing reacts the rest of the matrix into a lower index (clad) region. The polymer material must be chosen such that it has a negative dn/dT (preferably as large as possible, but $>2\times10^{-4}$/°C), with reasonably low loss (<2dB/cm), and the ability to induce a significant index change ($\sim1\times10^{-2}$) on exposure to light with a core index near 1.455 at 1550 nm. Most UV curable polymers develop increased index on photoexposure due to densification of the polymer. In some of the examples in this disclosure commercially available optical adhesive polymers such as Norland 81, Norland 63 or UV 3000 were employed. These are not optimal since the induced effect can be bleached by general photoexposure or thermal exposure. A preferred polymer, in which a permanent compositional change is developed during the UV exposure of the polymer, was developed for this application. In this composition three components were mixed into the liquid formulation to enable formation of the core/clad structure. The first component (I) is a cationic polymerizable fluorinated low refractive index solid polymer. This material enriches the low index cladding due to its slow reactivity during the UV curing process at room temperature. Due to its highly fluorinated structure, it is expected to readily phase separate from the hydrocarbon monomers that comprise the rest of the formulation. This drives the diffusion process required to define the channel waveguide boundary. The second composition (II), therefore, is a high index and highly reactive hydrocarbon liquid monomer. This composition will be locally enriched and polymerized in the path of the UV beam because of the high reactivity and diffusion coefficient comparing with the composition (I). The third composition is small amount of di-functional co-monomer which will engage in the both reaction and behavior like a compatibilizer to improve the structure stability. The final structure of polymer is an interpenetrating polymer network (IPN).

Specifically, the polymer formulation F-1, providing a compositionally stable core/clad structure, was formulated as follows. Fluorinated maleimide/fluorinated acrylate/glycidyl methacrylate copolymer (MIC#20 1.0 g RI =1.462 at 1550 nm) was dissolved into 1.5 g 1-4 butanediol dimethacrylate (RI =1.50-1.51 at for the homopolymer at 1550nm) and 0.3 g glycidyl methyacrylate on the hot plate. Then 26 mg cationic initiator (triaryl sulfonium hexafluoroantimonate salts) and 21 mg radical initiator (Radocur) were added into the liquid formulation. The clear solution was coated at the end of SMF-28 optical fiber. After curing under the UV lamp for ten seconds (120 mJ/cm^2), the polymer was post-baked at 150 °C for 15 mins. Measuring the reflection light intensity of the fiber/polymer interface, we can obtain the



value of dn/dT and corresponding glass transition temperature of cured material. The results from the plot showed a Tg ~160 °C and the dn/dT about 2.12 x10^{-4} between the temperature range of 30-140 °C. The average refractive index at 20 °C is 1.493.

Process for Fiber-to-fiber coupling

We used the following procedure to write a waveguide between two single mode SMF28 fibers. First, the fibers were stripped of the coating and cleaved. Next, the cleaved fibers were placed in a precision XYZ stage to control the alignment of the fibers. A drop of Norland NOA81 UV curable optical adhesive was placed on the ends of the fibers and the fibers were actively aligned at 1550nm to optimize the alignment of the cores. A gap of approximately 75-100 microns was left between the two fiber ends. The UV adhesive drop was flood cured with a low intensity UV lamp for 30seconds to pre-gel the adhesive. After pre-gelling, high intensity UV light from a Greenspot UV source was launched down both fibers simultaneously for two minutes to write the waveguide between the two fibers. The resulting written waveguide region is shown in Figures 1 and 2.

We demonstrated improved optical coupling between two SMF28 fibers using the UV end-firing curing technique. This technique was used to couple two SMF28 fiber ends that were clad aligned with a gap of 150µm. Before the waveguide was written between the two fibers, the IL was 4.68 dB. After the waveguide was written the IL was 1.37dB, an improvement of 3.4dB.

Process For Writing Waveguide in Groove

The process that was generally employed was to write a waveguide in a groove between two arms of a planar waveguide. A polymer was loaded into the groove and was characterized for loss at 1550 nm by close coupling two fibers to the ends of the a straight waveguide and measuring the power relative to a straight waveguide with no groove. Then a cure process was initiated which involved the following steps:

1) Pre-cure with a flooded low power UV source to increase the viscosity
2) End-fire cure through the waveguides with 365nm light coupled through SMF 28 fiber;
3) Postcure to rigidize the entire matrix;

Finally the loss at 1550 nm was measured to determine the waveguide efficiency in reducing loss from the free space propagation value.

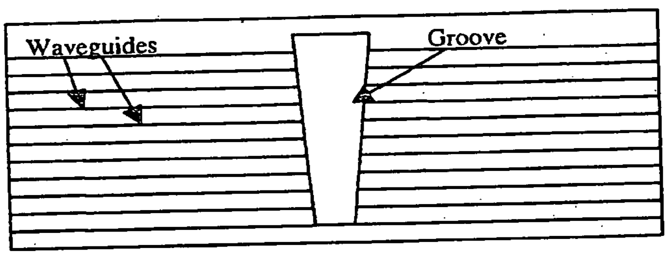
Steve Dawes
Ziyou WANG

Several experiments using the end-fire curing process to write waveguides in a polymer filled groove interrupting straight planar waveguide are presented here which succeeded in demonstrating nearly total elimination of diffraction loss. A LOC 57 device was used, where 60 straight waveguides, 2.2 cm long with a pitch of 40 microns, were interrupted with a deep etched triangular groove. The groove at the wide end measured 140 microns wide and at the narrow end measured 20 microns wide. The difference in the gap in the groove that each successive waveguide passes through is 2 microns. The geometry the device is shown below. Free space propagation through the groove causes a gap width (G_w) dependent loss which for an index oil filled groove follows the empirical relation:

$$\text{Loss}_{\text{oil}} = (\text{Coupling Loss}) + (\text{Propagation Loss})_{\text{oil}} + 0.047\text{dB}\ (G_w - 16\ \mu\text{m}).$$

If a waveguide is written between the inputs and outputs then the total loss should be independent of the groove width.

$$\text{Loss}_{\text{waveguide}} = (\text{Coupling Loss}) + (\text{Propagation Loss})_{\text{waveguide}}.$$



When and experiment was run, the power transmission was measured for close coupled optical circuit before and after the writing of a waveguide. The improvement in power transmission was compared to the gap width dependent loss to determine the efficiency of the waveguide. For the devices presented in this work, the coupling loss + Propagation loss is 0.8 dB +/- 0.3 dB, based on uninterrupted straight waveguide measurements.

One experiment is reported on a LOC 38 1x8 phasar, which successfully to showed that a single end-fire cure process could coincidentally write waveguides across each of the arms in a phase array.

Examples: Waveguides in Groove

Several examples of varying process conditions to write waveguides in the groove indicate the process parameters, and potential for this technique. The pre-cure step was found to be crucial to achieving low loss. A groove was filled with commercially available UV3000 optical adhesive. With a pre-cure time of 0 seconds a waveguide was written by end-firing for >360 seconds. The waveguide was well resolved, but was highly distorted , probably resulting from convection currents causing flow in the low viscosity clad region during the cure of the core. No reduction in loss for the waveguide was measured. Figure 3 shows a sample with more optimal pre-cure conditions, using Norland 63 optical adhesive in the groove. This polymer cures faster than the UV 3000, and was pre-cured for 8 seconds, and then end-fire cured for 120 seconds, with resulting improvement of 2.7dB from the original gap dependent loss of 3.6 dB. In this case the waveguide formed is straight and confined. Figure 4 shows an example of a sample pre-cured for too long before end-firing. The groove was filled with Norland 81, also fast curing, and was pre-cured for 30 seconds and end-fire cured for 20 minutes. Here a "bowtie" pattern formed in the polymer, showing the UV beam divergence across the entire gap width from both waveguides. The loss improvement measured in this example was 0.7dB relative to a gap width dependent loss of 4.8 dB.

The multi-component polymer, F1 which forms compositional gradients on UV curing was used to form low loss waveguides that could provide exceptional stability. This polymer was processed by coincident flood illumination and end-firing for 300 to 600 seconds. The sample was then heated to 100 C for 1 hour to complete the cure. Figure 5 shows a waveguide formed with the 300 second cure, through G_w= 96 μm. The loss improvement measured for this example was 3.6 dB recovering nearly all of the 3.7 dB diffraction loss.

Table 1. Results of representative waveguide writing experiments

	G1C- 10	G1C – 8	G1C-23	G1C-
Polymer	UV3000	Norland 81	Norland 63	F1
Loss calc from G_w	4.8	5.1	3.7	3.7
Loss Measured $_{oil}$		4.8	3.6	3.7
Loss after endfire cure	>5	4.1	0.9	0.1
Improvement	none	0.7	2.7	**3.6**
Process	End cure only	Pre-cure Endcure 20 min	Pre-cure 8 seconds End cure 60 seconds	Co-cure top and end 300 seconds

Finally a phasar was attempted using the basic processing principles described above. The major difference with this device compared to those previously described is that is that when the UV source is launched into the input and output fibers, it follows a path that first enters a slab waveguide with free space propagation before impinging on the phase array, a group of 50 to 100 waveguides that perform the grating function in the device. So for a given incident power the actual UV signal crossing any one path across the groove is about 1 to 5% of the original power. Figure 6 shows an optical micrograph of the phase array region filled with Norland 63, and exposed for 1 hour using multimode fiber end-fire curing (maximize UV power coupling into the planar waveguides), with low intensity flood curing. The micrograph shows 10 waveguides written with the single exposure at the wide end of the groove, each with a well formed waveguide. No loss measurements were possible on the device, because our on-line measurement can not resolve the low power of each output of the phasar, and the temporal stability of the optical adhesive waveguides are poor. We attempted to cure a phasar with the F1 formulation, but have not been able to optimize the conditions for forming waveguides in the slow curing polymer with low incident UV power in the phase array. This is not anticipated to be a fundamental limitation.

Other Applications

The process described here was developed in response to needs arising from athermalization of phase array WDM devices and fiber to fiber splicing. The key elements are that a low cost process is used, and low optical loss can be achieved. In the case of the phasar devices this technology could be used to athermalize the output wavelength positions. In fiber to fiber splicing this technique can be used to couple light between fibers with significantly different material properties, where fusion splicing is difficult to impossible. Other applications can be easily envisioned as falling within the scope of the invention. Thermo-optic devices made by replacing a section of silica planar waveguides, for example in one arm of a Mach Zehnder device, with UV waveguidable polymer with large negative dn/dT could be used to maintain low loss and to reduce switching power by a factor of 25. Issues with multiple grooves in a single

pass would have to be addressed. Also the potential of reducing coupling loss in fiber to fiber bonds where the two fiber have poor mode field match characteristics could have significant utility.

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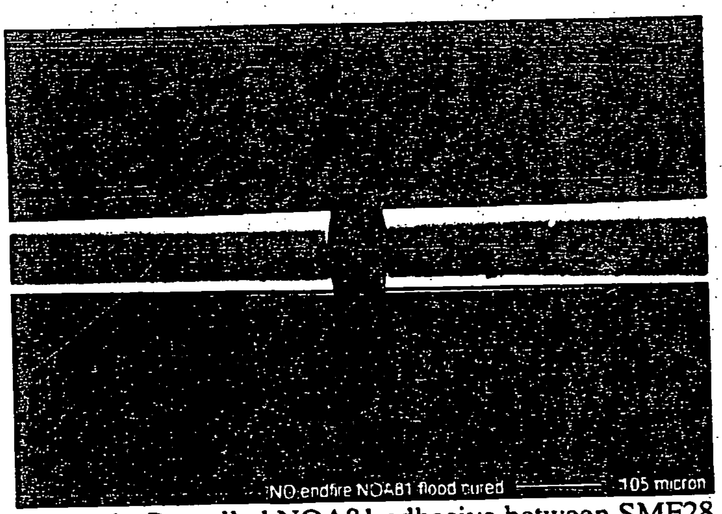


Figure 1. Pregelled NOA81 adhesive between SMF28 fibers before endfire curing.

Ziaoyu WANG

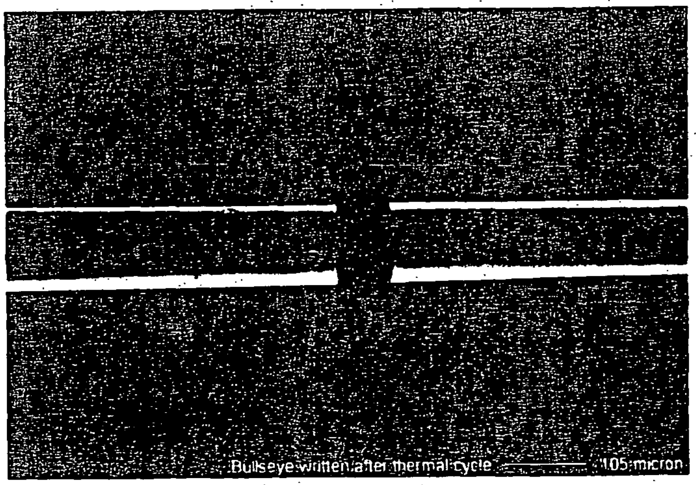
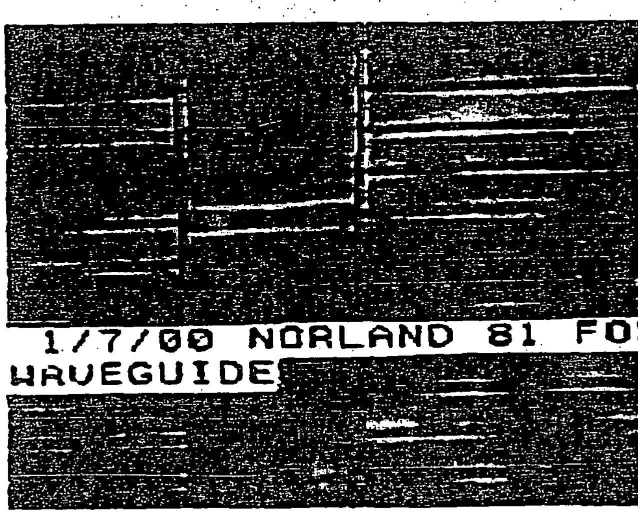


Figure 2. Waveguide between two fibers after endfire curing.



"Bowtie" waveguide in groove

Figure 3. Micrograph showing waveguide in groove with excessive pre-cure. Note "bowtie" shape of guides.

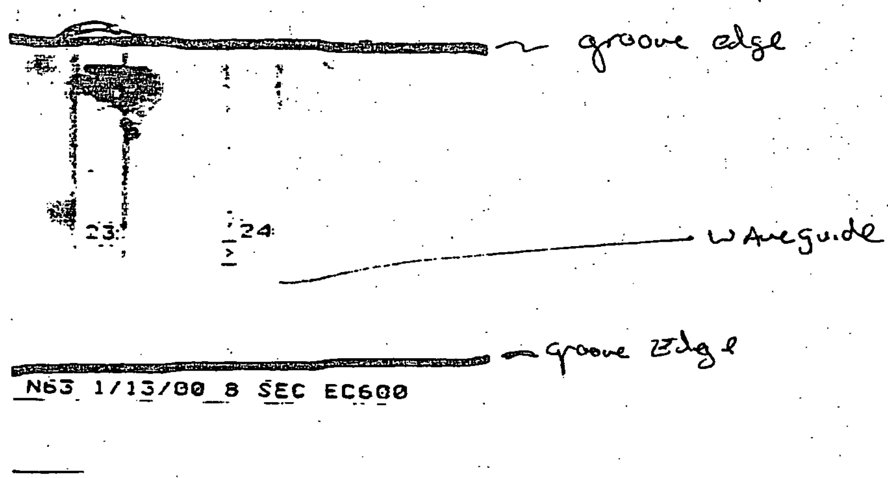


Figure 4. Micrograph showing waveguides in groove written in Norland 63. Loss reduction from 3.5 dB to -.9 dB.

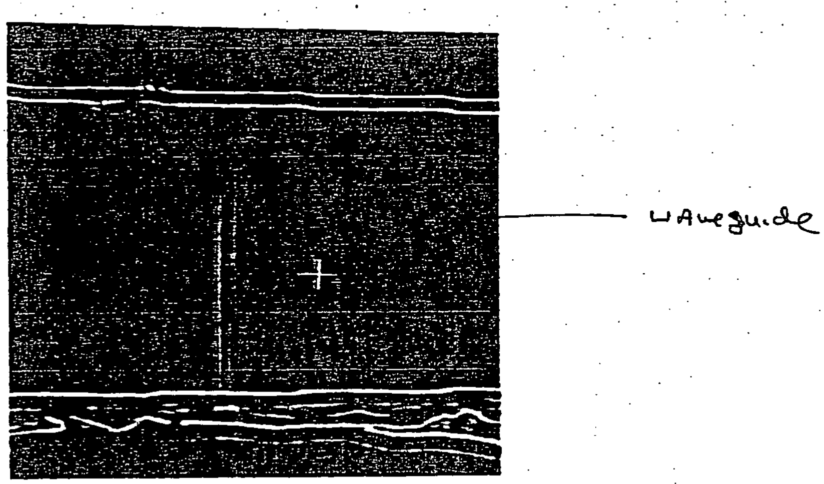


Figure 5. Waveguide in groove written in F1 polymer. Diffraction loss after cure is <0.1dB.

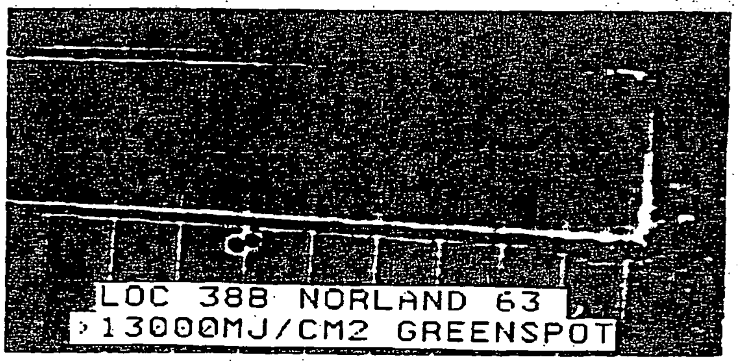


Figure 6. Waveguides in phasar groove written in Norland 63. Sample was made with one end-fire cure through a single input. Note that all 10 waveguides in phase array have well defined waveguides in the groove. No loss measurements available.

Jiap WANG